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Research article

CO_2 capture and storage: A way forward for sustainable environment

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ABSTRACT

The quest for a sustainable environment and combating global warming, carbon capture, and storage (CCS) has become the primary resort. A complete shift from non-renewable resources to renewable resources is currently impossible due to its major share in energy generation; making CCS an imperative need of the time. This study, therefore, aims to examine the reckoning of carbon dioxide (CO_2), measurement methods, and its efficient capture and storage technologies with an ambition to combat global warming and achieve environmental sustainability. Conventionally, physical, geological and biological proxies are used to measure CO_2. The recent methods for CO_2 analyses are spectrometry, electrochemical gas sensors, and gas chromatography. Various procedures such as pre, post, and oxyfuel combustion, and use of algae, biochar, and charcoal are the promising ways for CO_2 sequestration. However, the efficient implementation of CCS lies in the application of nanotechnology that, in the future, could provide a better condition for the environment and economic outlooks. The captured carbon can be stored in the earth crust for trillions of years, but its leakage during storage can raise many issues including its emissions in the atmosphere and soil acidification. Therefore, global and collective efforts are required to explore, optimize and implement new techniques for CCS to achieve high environmental sustainability and combat the issues of global warming.

1. Introduction

The excessive release of carbon dioxide (CO_2) from industries, power plants, and other sources is playing a critical role in the global climate and Earth's life cycle (Al-Maamary et al., 2017). CO_2 concentration has increased from 280 to 400 ppm with 0.8 °C increase in global surface temperature (Pachauri et al., 2014). Recently, CO_2 concentration has mounted up to a keeling curve of 408.8 ppm (Kumar et al., 2017), with a prediction of 600–700 ppm at the end of this century leading to an increased average surface temperature of 4.5–5 °C (Leung et al., 2014). The critical factors affecting CO_2 concentration are uncertain economic, sociological, and technological changes along with human and natural developments (Nakicenovic et al., 2000).

The emissions of other greenhouse gases (GHG), besides CO_2, including methane (CH_4), nitrous oxide (N_2O), hydro-fluorocarbon (HFC), perfluorocarbons and sulfur hexafluoride (SF_6) have also increased drastically during last few decades (Al-Maamary et al., 2017; Ouda et al., 2016). Intergovernmental Panel on Climate Change (IPCC) believes that in order to prevent our planet from a catastrophic collapse, there should be 50–80% reduction in GHG emissions by 2050 (Pachauri et al., 2014). Around 190 countries were gathered in Paris (Conference of Parties-COP 21) during December 2015 to limit the CO_2 concentration for controlling the average temperature rise to 2 °C by the end of this century. The recommended strategies by COP 21 include promoting energy conservation and efficiency, employing renewable and low carbon fuels, adapting geoengineering strategies like afforestation, and most importantly developing CO_2 capture and storage (CCS) techniques (Leung et al., 2014; Kumar et al., 2017). Consequently, CCS is widely accepted as a promising tool, if not ideal, in lowering the global CO_2 emissions (Chalmers and Gibbins, 2007; Odenberger and Johnsson, 2010).

Globally, CO_2 emitted from power plants is around 40% of the total CO_2 emissions (Alonso et al., 2017) and under business as usual model, it is expected to increase up to 60% by the end of this century (Kumar et al., 2017). The transportation sector is responsible for about 20% of the total global CO_2 emissions. Similarly, building and agriculture sectors are contributing around 17% of total CO_2 emissions (Pachauri et al., 2014). CO_2 concentration due to forestry and other land use

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(FOLU) has reduced from 17 to 11%, whereas there is 10% increase in CO_2 concentration due to fossil fuel burning from 1970 to 2010. If all the forested area is recovered, it will only mitigate 11% of the global CO_2 emissions, while 65% emissions that are coming from fossil fuel burning will remain the primary strategic issue (Pachauri et al., 2014). Therefore, new and efficient technologies like CCS for fast removal of CO_2 from the atmosphere in order to combat global warming has gained significant attention in recent years.

CCS is mainly dependent upon the type of combustion process and volume of CO_2, its absorption, separation, and transportation for storage or reuse purposes (Leung et al., 2014). CCS technologies can help in restricting the global average temperature rise to 2 °C by reducing CO_2 emissions from different energy-intensive facilities (Leung et al., 2014). The main CCS technologies include post, pre, and oxyfuel combustion, while the post-combustion is the most mature technology. Coal gasification is the economic CCS technology for CO_2 capture, but it is not suitable for gas-fired plants. It is a retrofit technology as it utilizes most of the infrastructure of the existing power plant. At small scale, it has proved to recover CO_2 at a rate of 800 t/day (Leung et al., 2014).

In oxyfuel combustion, the use of pure oxygen instead of air eliminates the need for de-NOx of flue gas that contains 80–98% CO_2 thus making it an efficient technology for CO_2 removal. However, the process is energy intensive along with the intensification of the corrosion process due to high SO_2 concentration (Araújo and de Medeiros, 2017). In pre-combustion CCS, fuel is pretreated in a gasifier under low O_2 pressure, and syngas ($CO + H_2$) is produced (Leung et al., 2014). Due to the high concentration of CO_2 in the fuel gas, its separation becomes easier than other techniques with the production of H_2 as an energy carrier. This offsets the operational cost of technology to some extent (Araújo and de Medeiros, 2017). The CCS technologies still require further improvements to tackle the limitations of high cost, insufficient investment, lack of incentives, and infrastructure (Kumar et al., 2017), which was the focus of this study.

This paper aims to examine the recent trends in CCS technologies with an ambition to significantly reduce the CO_2 emissions in order to combat global warming and achieve environmental sustainability. The measurement of CO_2 and the factors affecting its measurement are also discussed in detail. The findings would develop a thorough understanding of different proxies being employed to reconstruct past climatic conditions, as both CCS and CO_2 measurement techniques are critically reviewed in this study.

2. CO_2 measurement methods

Scientists employ proxies to construct past climate since instrumental record dates to a post-industrial era only (Mann, 2002; Li et al., 2010). These proxies are divided into physical, biological, glaciological, chemical and geological proxies (Fig. 1). Out of these, some are engaged in measuring paleo CO_2 directly, whereas other proxies can measure it indirectly (Readinger, 2006; Gornitz, 2009; Kaufman et al., 2016). All these proxies are beneficial at the individual level with multiple benefits. However, data with high resolution and well-dated information can only be obtained by employing a multi-proxy approach as individual proxies have some limitations as summarized in Table 1.

2.1. Physical proxies

Careful examination of physical properties of rocks can reveal the climatic setting at the formation period (Gornitz, 2009). For example, rust color indicates oxidation and sea level change, green color exhibits some photosynthetic activity, and the white color depicts the bleaching phenomenon. Texture tells how sediments are transported; how far they are brought here and lastly how were the energetic environmental conditions such as wind speed and water flow. If the rock has coarse sand grains, then it is formed under turbulent conditions. Conversely, if the sediment contains smaller clay particles, then it is formed under calm and still conditions (Beus and Morales, 2003; Gornitz, 2009). Shape and thickness of sediment layer provide plenty of information about conditions under what these were deposited, suitable conditions for biological activity, the direction of the wind and water flow, and the pattern of deposition (Beus and Morales, 2003; Gornitz, 2009). Source of sediments can easily be identified by measuring its ease of magnetization; if it readily gets magnetized, then it is by some volcanic eruption or some geological unit containing elements like iron (Gornitz, 2009; Maxbauer et al., 2016). The physical proxies give a birds-eye view of the climatic conditions of past. However, scientists need to seek help from other proxies as discussed below in order to build some authentic opinion.

2.2. Glaciological proxies

The ice sheets deposited at all continents, especially in Antarctica and Greenland in the forms of glaciers can serve the purpose of historical CO_2 concentration measurement for the period dating back to hundreds of centuries. There are two primary projects launched; one is the Greenland Ice Core Project, and other is the Vostok Ice Core Project. Antarctica is providing data up to 0.1 and 0.4 million years respectively (Readinger, 2006; Kaufman et al., 2016). Scientists drill deep holes into the ice sheet having 4–5 inches diameter and 1-meter length and study the composition of air and dust trapped inside the extracted ice cores by gas chromatography (Mann, 2002; MacFarling Meure et al., 2006; Veettil et al., 2017). Age-depth relationships are determined by employing ice flow models, radio-isotopes dating and chrono-stratigraphic markers (MacFarling Meure et al., 2006; Veettil et al., 2017). The first one is exponential, for instance, the first thousand meters specifies 50 thousand years and following 50 meters may stipulate 0.1 million years due to deformation and immense compaction (Readinger, 2006). Hence, one can get accurate measurements up to 10 thousand years only (Kaufman et al., 2016; Veettil et al., 2017). The decay of radioactive isotopes of oxygen and hydrogen occurs at a constant rate after alpha and beta emissions are employed to date ice cores (Readinger, 2006; Veettil et al., 2017). Annual layers and reference horizons, in the form of chronostratigraphic markers, provide information about seasonal variation and major volcanic eruptions. These eruptions injected a significant amount of SO_2 and ash into the atmosphere (MacFarling Meure et al., 2006; Readinger, 2006; Li et al., 2010). The influx of SO_2 hence reduces pH of snow layers that is measured by electrical conductivity method (Veettil et al., 2017). Ice lenses and glands are formed due to melting feature in the upper layer of glaciers. Their relative frequency explains the peak summer temperatures. These structures are easily identified because of air bubbles deficiency (Readinger, 2006). Furthermore, ice cores are used to predict several meteorological parameters like amount of precipitation, solar activity, sea salt concentration, air temperature, atmospheric composition, and atmospheric circulation variations (Abram et al., 2013; Veettil et al., 2017).

2.3. Stable isotopic measurement

Oxygen has three isotopic forms such as ^{18}O, ^{17}O, and ^{16}O with the relative abundance of 0.2%, 0.04%, 99.76% respectively (O'brien et al., 1995; Readinger, 2006). Water molecules ($H_2{}^{16}O$) are lighter with higher vapor pressure and low vaporization energy with a high concentration in clouds as compared to $H_2{}^{18}O$ (McDermott, 2004; Kaufman et al., 2016; Shao et al., 2017). Conversely, as the air mass moves towards the poles, the condensation occurs, and heavier molecules due to their lower vapor pressure preferentially condense. Thus, precipitation become richer, and clouds are more depleted in heavier molecules (Readinger, 2006; Kaufman et al., 2016; Veettil et al., 2017). Air temperature will determine the concentration of heavier molecules in the condensate (Readinger, 2006). This temperature dependence of oxygen isotope makes it a good climate proxy (Readinger, 2006; Li et al., 2010; Mayewski et al., 2017). Based on the facts mentioned above, it is

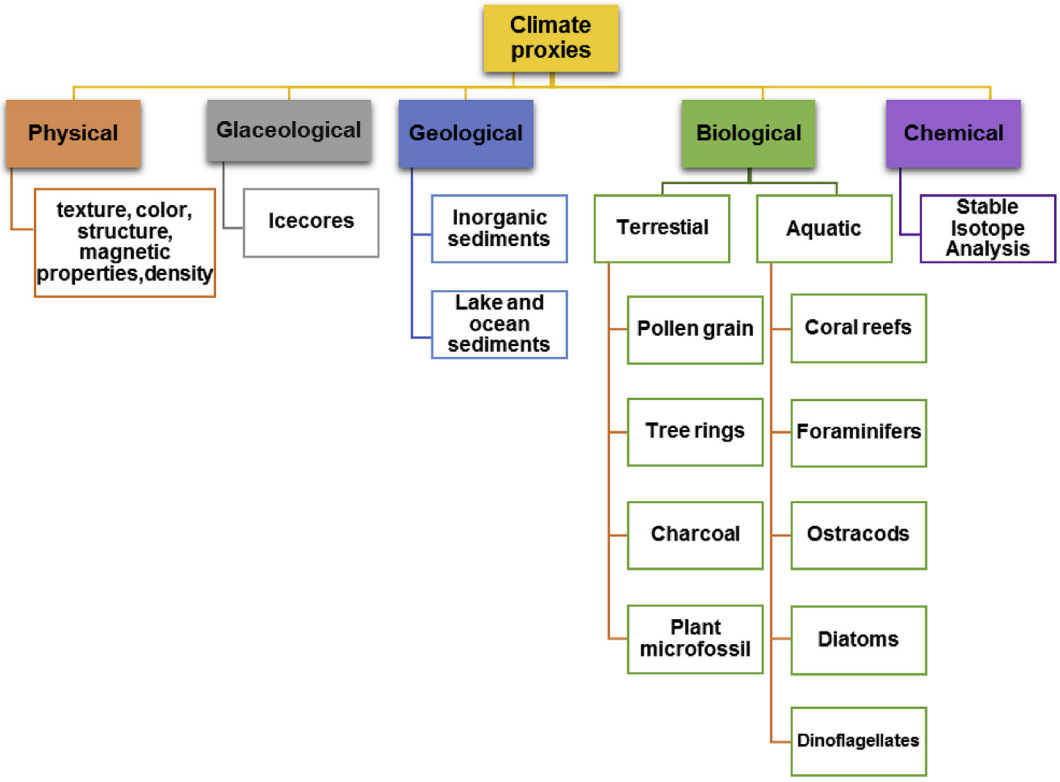

Fig. 1. Different direct and indirect proxies used by scientists to predict paleo-climate.

inferred that ice enriched in lighter molecules of water was formed at low temperature and vice versa; depicting the atmospheric CO_2 concentrations (Charles et al., 1996; Readinger, 2006).

2.4. Biological proxies

There are various biological proxies used to measure CO_2 such as tree rings, pollen grains, coral reefs, and sediments of deep ocean and lake.

2.4.1. Tree rings

Density, isotopic composition, and width of tree rings are studied for reconstruction of prehistoric climatic conditions and age of the respective trees (Schultz and Neuwirth, 2012; Saito et al., 2015; Esper et al., 2016). One growth ring is formed annually; comprising of early wood formed during summer and latewood during winter (Smith, 2008; Singh et al., 2017). This annual periodicity is more evident in the trees grown in temperate regions than in tropical region due to the distinct growing season (Smith, 2008; Esper et al., 2016). However, one needs to take care of certain criteria before employing a specific tree for CO_2 dating. It must be present in its wild habitat, not affected by humans, and should be healthy (Singh et al., 2017). Corers might be used for the sample collection from the oldest trees, as they provide prolonged data. Currently, climatologists employ two approaches for analysis (Smith, 2008). They correlate the results obtained from both living and dead (fossils) trees to limit down the element of uncertainty (Li et al., 2010; Árvai et al., 2016). Radiocarbon dating has been employed to get accurate results in case of fossils due to the logarithmic decline of ^{14}C at a constant rate after the plant's death (Charles et al., 1996; Árvai et al., 2016).

Table 1
Limitations of different proxies used to construct past climate.

Proxies	Limitations	References
Ice cores	• Melting of ice sheets during summers (more triggered recently due to global warming) disturbs the regular layering and chemical composition of ice, making accurate dating impossible. • They provide data accurately up to 10,000 years only due to immense compaction and deformation. • The irregular surface of bedrock causes basal deformities which propagate to upper layers, making accurate dating impossible. • Moreover, they only provide paleo record of polar and high-altitude areas.	(McDermott, 2004; Mann, 2002; MacFarling Meure et al., 2006, Readinger, 2006; Gornitz, 2009; Kaufman et al., 2016; Mayewski et al., 2017)
Tree rings	• This proxy is geographically limited to subtropical and tropical regions only. • Volcanic forcing causes reverse summer and winter temperatures. So, the same species in the same era will provide different records.	(Mann, 2002; Smith and Lewis, 2007; Smith, 2008; Li et al., 2010; Singh et al., 2017)
Pollen grains	• It only provides information about the species having pollens but not about herbs, shrubs, and grasses.	(Mann, 2002)
Corals	• It only provides climatic records of tropical and subtropical coastal areas. • Sometimes non-climatic reasons also influence their growth, but no link is established to encounter this problem.	(Mann, 2002)

2.4.2. Pollen grains

Vascular plants have a unique reproductive structure called pollen grains that are stable and robust. They have a unique shape, and a size in the order of 10–200 microns made up of a substance called sporopollenin (Griener and Warny, 2015; Li et al., 2016a,b). Due to their lightweight, they are easily washed away by water and are preserved in sediment layers (Griener and Warny, 2015; Xu et al., 2016a,b). Scientists drill out core samples from the sediment layers and identify the type of pollen in each sediment layer by using different physical and chemical methods. After, they draw diagrams, and calculate the abundance of specific pollen, and determine the type of vegetation present at the time when sediment layer was deposited (Griener and Warny, 2015; Parnell et al., 2016). The abundance of pollen in a sample refers to abundant species. Since each species grows in specific climatic condition, so one can easily predict the climate of that time. Fossil pollens are a direct proxy of past vegetation and indirect for past climate. However, the relationship between vegetation, climate, and pollens are not linear. Hence, quantitative reconstructions are difficult, and results might be contradictory (Griener and Warny, 2015; Xu et al., 2016a,b). Moreover, by comparing the vegetation of thousands of years ago to present day vegetation scientists not only can tell the paleoclimate but also the impact of anthropogenic activates on climate as well.

2.4.3. Coral reefs

Small creatures called polyps build corals, and they live in the form of colonies forming coral reefs (Druffel, 1997; Felis and Pätzold, 2004). Some are hard in a structure made up of a mineral called calcite, or calcium carbonate and live in shallow, clear, warmer, and nutrient-rich water. They only bloom in the tropical and subtropical areas (Felis and Pätzold, 2004). This delicacy to climatic conditions makes them good low altitude proxy complimenting the data obtained from high and moderate altitude proxies. The ice cores and tree rings are providing continuous paleoclimate records form centuries to millennia. Corals contain layered structure with dark bands depicting winter and lighter bands indicating summer. However, unlike tree rings, it is not the width of the calcite layer that helps scientists to predict past climate but the composition of the mineral (Felis and Pätzold, 2004). Corals require calcium and carbonate ion to build their shells, but ocean acidification triggers the formation of hydrogen carbonate instead of carbonate ion. This makes shells to dissolve to keep carbonate level balanced and grow less and change shell composition (Carré et al., 2012). Scientists drill out the sample and analyze it by employing X-ray imaging.

2.4.4. Deep ocean and lake sediments

Another relevant methodology for the CO_2 dating is the analysis of deep ocean and lake sediments (Felis and Pätzold, 2004). Foraminifers are tiny, marine, microscopic, and shelled organisms. They harvest oxygen with a fixed ratio of lighter and heavier oxygen atom. For instance, 500:1 calcium and carbonate ion from seawater is used to build their shells and become part of ocean sediments when dead. Scientists calculate this ratio to figure out the volume of ice on mountain tops and glaciers, and from this, the average global temperature is calculated. By drilling a long core from ocean sediments, one can get a continuous record of temperature fluctuations over the past hundreds to millions of years (Charles et al., 1996, Felis and Pätzold, 2004).

2.5. Atmospheric CO_2 measurement

Mauna Loa Observatory (MLO) Hawaii is an atmospheric research facility located at about 3400 m above sea level. The facility is ideal because of the remote location, undisturbed air, little influence of humans and less vegetation. The National Oceanic and Atmospheric Administration (NOAA) and Scripps are continuously monitoring and collecting data related to atmospheric change since 1950's. Scripps project, launched by David Keeling at Scripps Institution of Oceanography, was first entitled to the measurement of the present level of CO_2. However, later, its scope was widened to prehistoric ages dating back to 400,000 years via employing polar ice cores method. The careful reconstruction of the CO_2 level of the past many millennia has revealed its constant low amplitude with 200 ppm and 280 ppm during ice ages and interglacial periods respectively. However, due to the anthropogenic activities, the current level of CO_2 has reached the alarming level of 408.8 ppm (Keeling curve). At MLO, the air sample is collected at 40-meter-tall tower and analyzed by IR gas analyzer. The air is slowly pumped through a cylinder having windows on both sides. IR light enters from one window, and after passing through the sample, it exits through the second window and falls on the detector. Here scientists primarily measure the mole fraction of CO_2 in dry air and not the concentration, as the purpose of this project is to quantify how much CO_2 is entering the atmosphere. Mole fraction (dry air) gives the more accurate value as it does not depend upon the pressure and temperature of the gas sample. The instrument is calibrated after an hour to maintain the accuracy with three reference CO_2 samples. Another technique called light detection and ranging (LIDAR) employs a laser beam of high intensity to monitor the stratospheric aerosols made up of water and sulfuric acid. Once in a week, a powerful pulsed beam is bombarded at the particles to create a high-resolution vertical profile of stratosphere. The scattered laser light from the particles is measured with the help of telescopes. The aim is to have a laser beam at different angles, and a total number of aerosols and their cooling effect is hence calculated. The CO_2 measurement is further interpreted to predict the atmospheric temperature. Tropospheric CO_2 is also measured by using the balloon method through two geographic positioning system (GPS) sensors. CO_2 sensor, recording devices, and a parachute were tied to a balloon filled with helium in these sensors. The CO_2 sensors measure the molar density of CO_2 by IR absorption. It primarily uses the ideal gas law to measure the pressure, temperature, and molar density of air. From this, the relative concentration of CO_2 in ppm is measured. One GPS sensor measures the temperature, relative humidity, pressure, and altitude, and it transmits the radio signal to the chasing vehicle. The other sensor serves as a backup for the primary sensor. The measurement is observed in the form of visual output on a computer screen. In chemical method, a sample from the atmosphere is sucked into a pH-sensitive chemical, and variation in color is observed following the principle of litmus paper with purplish and yellow color depicting high and low concentration of CO_2.

3. CO_2 capture technologies

There are multiple approaches to capture CO_2 that are discussed under the umbrella of post-combustion, pre-combustion and oxyfuel combustion (Leung et al., 2014). Pre-combustion is a relatively easy and widely employed approach that favors the high volume at a ratio of 10:1. Whereas, the post-combustion technique is efficient at the lower stream of CO_2 (Sreedhar et al., 2017). A combination of integrated gasification combined cycle and a shift reactor for the conversion of carbon to CO_2 is employed in pre-combustion CCS (Song et al., 2012; Wall, 2007). Table 2 explains different classes of CO_2 capture and storage.

3.1. Post-combustion

It involves the abduction of CO_2 from flue gas after combustion using a suitable adsorbent like amine (Leung et al., 2014; Ben-Mansour et al., 2016). It is comparatively appropriate technology to capture CO_2 in natural gas production plants since last six decades. It uses various amine solutions like mono-ethanolloamine, di-ethanolamine, potassium carbonate and methyl-di-ethanolamine as separating agents (Olajire, 2010). Novel sorbent piperazine is used nowadays to efficiently capture the pollutant due to its high volatility (Bougie and Iliuta, 2011). CO_2 is firstly lodged in the solution by chemical reaction and is separated by the passage of steam through it under high temperature (100–200 °C).

Table 2
Different classes of CO_2 capture and storage (Scott et al., 2013).

Classes	Explanation
Carbon positive	The release of a significant amount of carbon when the process of combustion takes place such as coal to liquid, refineries and natural gas processing. EOR operations are sometimes carbon positive depending on the project specifics.
Carbon neutral	Conversion of carbon into CO_2 that can be used to produce commercial products
Carbon negative	Removal of CO_2 from the atmosphere directly or by this process applied to biomass combustion for generation of electricity

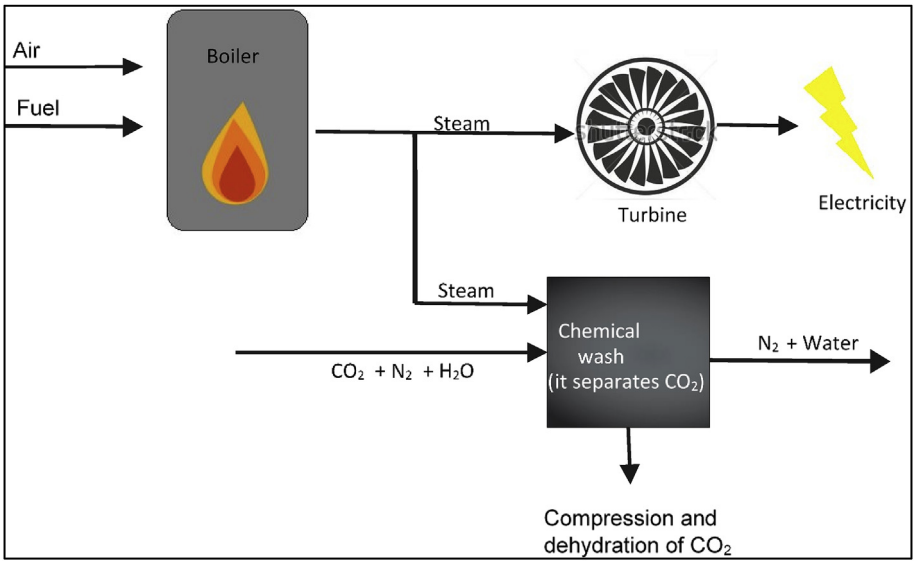

Fig. 2. Schematic diagram of a post-combustion technique used to capture CO_2 (Zero Emissions, 2016; Leung et al., 2014).

Following equation describes the reversible reaction containing both absorption and regeneration (Olajire, 2010).

$$C_2H_4OHNH_2 + H_2O + CO_2 \leftrightarrow C_2H_4OHNH_3^+ + HCO_3^- \quad (1)$$

This methodology, however, has certain limitations such as substantial parasitic load, the high temperature of flue gas, and un-operational at low CO_2 level. A generalized mechanism of post-combustion is illustrated in Fig. 2. Around 4% CO_2 is used in gas-fired, and 7–14% for coal-gas fired power plant, raising the electricity cost to 65% and 32% by coal and gas-fired power plant respectively (Leung et al., 2014). Therefore, lowering the cost without affecting the performance of the system remains the active area of research (Song et al., 2012). Post-combustion capture of CO_2 can also be achieved through membrane technology including polymeric or ceramic membrane, or through cryogenic distillation and marine algae. This offers a range of benefits like retrofitting and eliminating the need of shift reactor and cryogenic separator. The most commonly applied method for post-combustion is absorption-desorption of CO_2 using the alkanol amine solution (Kazemi and Mehrabani-Zeinabad, 2016; Li et al., 2016a,b).

3.2. Pre-combustion

This approach captures CO_2 before combustion and is considered comparatively more viable than post-combustion. It involves a gasifier and catalytic reactor. The following equations (Eqs. (2)–(4)) explain, firstly, pure syngas (CO, H_2) is formed in the gasifier, under low oxygen pressure. Secondly, to enrich syngas, it is passed through steam in the shift reactor as shown in Fig. 3.

$$2C + 3H_2O \rightarrow 3H_2 + CO + CO_2 \quad (2)$$

$$C + H_2O \rightarrow H_2 + CO \quad (3)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (4)$$

In this process natural gas can also be used for steam reforming, an endothermic reaction occurs at 700–850 °C, where the conversion of CH_4 and H_2O occurs yielding syngas (CO, H_2, CO_2). Afterwards, partial oxidation involves an exothermic reaction (Eqs. (5) and (6)) where the passage of CH_4 through oxygen yields CO_2 (Olajire, 2010).

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (5)$$

$$2CH_4 + O_2 \rightarrow CO_2 + 4H_2 \quad (6)$$

One of the important methods of pre-combustion is hydrated gas separation, that is nowadays the promising technique for pre-combustion (Xu and Li, 2014).

3.3. Oxyfuel combustion

In this method, pure oxygen is obtained from the air separation unit, and coal and flue gas are introduced in the oxyfuel boiler (Wall et al., 2009; Toftegaard et al., 2010; Chen et al., 2012). Coal is burnt under specific temperature and pressure. Due to the absence of nitrogen and excess of oxygen, the flue gases only contain CO_2 and water vapors as illustrated in Fig. 4. This also eliminates the need for cleaning the large volume of flue gas for de-NOx and de-sulfurization (Buhre et al., 2005; Stanger and Wall, 2011). Water vapors are condensed to maintain the temperature of the boiler. CO_2 is dehydrated, compressed and transported to a storage site or industries for carbonation of beverages, a solvent material, and used in fire extinguishers (Chen et al., 2012). A small portion of this flue gas is reused in raw form to maintain the internal temperature of the boiler (Toftegaard et al., 2010). It is the most efficient and retrofit technology for carbon capturing as compared to other methods (Kunze and Spliethoff, 2012). However, the process still encounters many challenges. Firstly, it uses a large amount of energy to obtain almost pure oxygen from the air separation unit (ASU), as it works on cryogenic distillation. This can substitute the integrated gasification combined cycle (IGCC) step that converts CO to CO_2

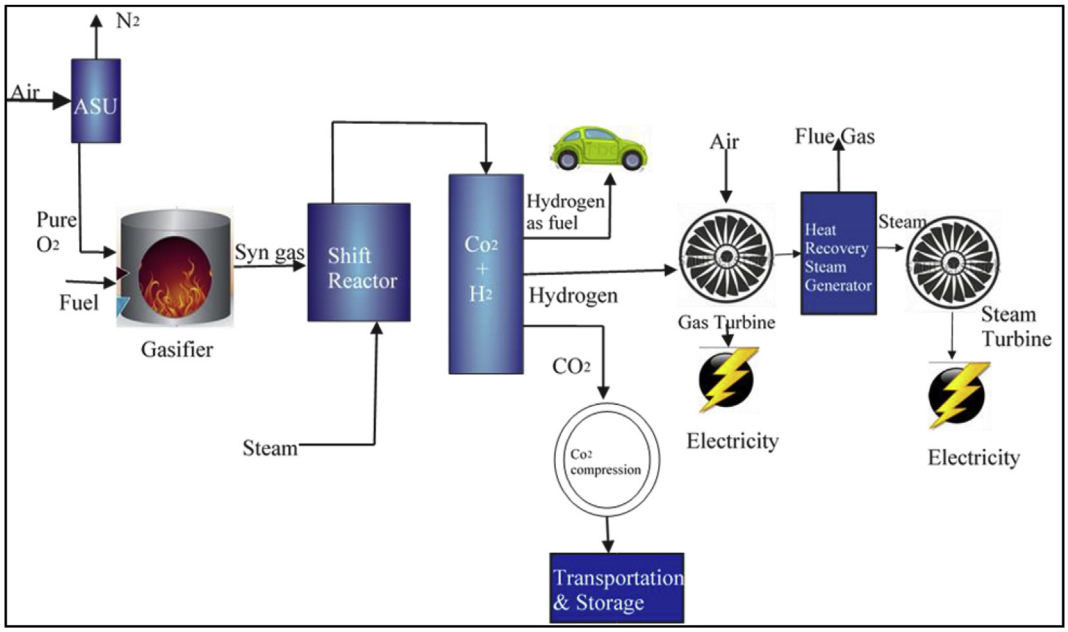

Fig. 3. CO_2 capture and storage by the pre-combustion technique (Zero Emissions, 2016; Leung et al., 2014).

somewhat offsetting the energy cost (Buhre et al., 2005; Wall, 2007; Habib et al., 2011). It is expected that in near future research can make this process feasible like the ion transport membrane (Wall et al., 2011). Furthermore, this process can be made carbon negative if biomass is used as a fuel source instead of other conventional fossil fuels (Wall et al., 2011). This offset the effect of CO_2 entering the atmosphere through anthropogenic activities (Toftegaard et al., 2010).

3.4. CO_2 capture by algae

Algae, the vital carbon sink, needs certain favorable conditions to grow such as pH, light, water, temperature, nutrients, and CO_2 as shown in Fig. 5. A hundred ton of microalgae can fix 183 ton of CO_2 (Zhou et al., 2017a,b). Simple structure with enhanced CO_2 fixation efficiency and faster growth rate makes microalgae an efficient sink for CO_2 as compared to terrestrial plants. Utilization of wastewater as the raw material makes it more eco-friendly as well as economical method (Ghosh and Kiran, 2017). Several species such as, *Chlorella* sp., *Botryococcusbraunii, Scenedesmus obliquus, Chlorella Vulgaris, and Scenedesmus* sp., can assimilate CO_2 and produce high qualities of lipids that are essential for biodiesel production. The most common method is the continuous supply of CO_2 through macro-bubble. Comparative study of micro-bubble (diameter: 1–2 mm) and macro-bubble (diameter: 10–50 mm) has proved the former more efficient because of the release of a significant amount of CO_2 back into the atmosphere. Photo-bioreactors are one of the essential components of its production as it has a substantial supply of CO_2 and light. Both open and closed systems are utilized for this purpose (Lam et al., 2012).

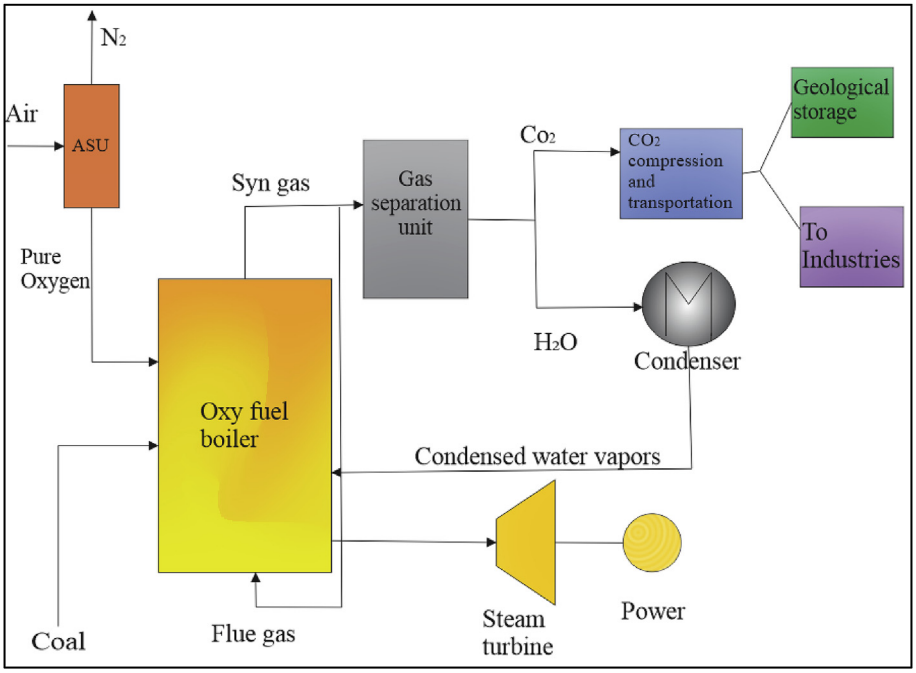

Fig. 4. Schematic diagram of CO_2 employing oxyfuel combustion technique (Zero Emissions, 2016; Leung et al., 2014).

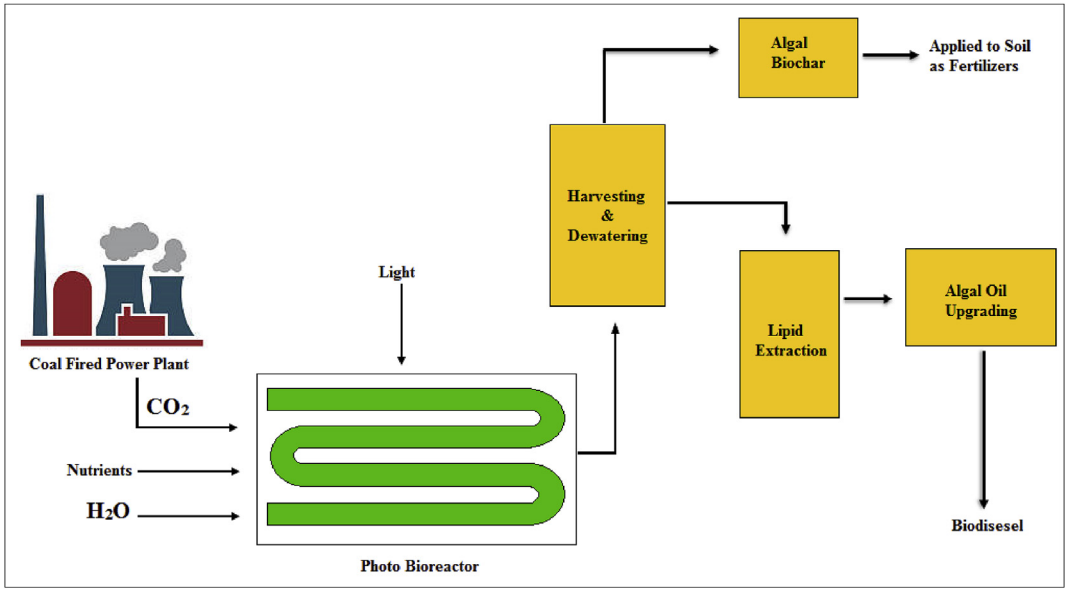

Fig. 5. Simplified flow diagram of CO_2 capture employing algae.

Continuously stirred tank reactors for carbon uptake are more efficient than high rate ponds. Several parameters should be considered while selecting suitable algae species, light intensity, temperature tolerance and CO_2 assimilation capacity (Moreira and Pires, 2016). Studies have shown the efficiency of different marine algae species for photosynthetic carbon uptakes such as *Fucus distichus* (captures 26,880 mg $m^{-2}day^{-1}$), *Iridaea flaccida* (9840 mg $m^{-2}day^{-1}$), *Prionitis lanceolata* (7296 mg $m^{-2}day^{-1}$), *Porphyra perforate* (22,560 mg $m^{-2}day^{-1}$), *Iridaea flaccida* (9840 mg $m^{-2}day^{-1}$), and *Ulva expanse* (13440 mg $m^{-2}day^{-1}$) (Tsai et al., 2017). When *Spirulina* sp. and *Scenedesmus obliquus* were grown in a photo-bioreactor at 30 °C, they have shown efficient results for capturing carbon (Ghorbani et al., 2014).

3.5. CO_2 capture through nanotechnology

Nanotechnology is defined as the purposeful manipulation of matter at the nanoscale of 1–100 nm (Yave et al., 2010). It yields a couple of significant advantages such as specific physiochemical properties and large active surface area to volume ratio (Alonso et al., 2017). Nanomaterials are classified into four groups like nano-composites, nanoporous, nano-crystalline and nano-hollow structure materials. Nanomembranes show high sorption rate as compared to other sorbents as these are fabricated using different nano-materials as precursors. However, membrane permeability and selectivity depend on the gas that is targeted for adsorption. These nanomaterials are nano-sized zeolites, metal-organic framework (MOF) with embedded nanoparticles, carbon nano adsorbents, and mesoporous silica nanoparticles. The pore size of 4–10 nm is used to capture water, alkanes, and CO_2 (Alonso et al., 2017).

Zeolites are crystalline, porous, three dimensional, highly ordered aluminosilicates that have alkaline earth and alkali elements with pore size ranging from 0.5 to 1.2 nm (Ashley et al., 2012; Choi et al., 2016). These are used to separate CO_2 from the air due to their great adsorption capacity which is 4–300 mg of CO_2/g at mild conditions. However, at a high temperature this ability decreases (Alonso et al., 2017). Zeolites are modified to nanoscale following the method of Jiang et al. (2013). The modification increases the sorption capacity due to an increased surface area that in turn have more active sites for adsorption (Jiang et al., 2013; Alonso et al., 2017). MOF has metal cation as the central atom, linked with different organic molecules forming a three-dimensional crystalline structure (Venna and Carreon, 2015). Several modifications in the structure are made to increase the CO_2 adsorption capacity such as functionalizing the pore surfaces with amines and incorporation of carbon nanotubes, nano-hollow structures with < 100 nm in length and 0.8–2 nm in diameter (Xiang et al., 2011). With all the promising aspects it offers, nanotechnology still needs to be tested in real case scenario (Alonso et al., 2017).

3.6. CO_2 capture via biochar

Biochar plays a significant role in the CO_2 capture, wastewater treatment, and energy storage (Waqas et al., 2018). Biomass resources produce it via thermochemical processes in the absence of oxygen such as gasification, pyrolysis, flash carbonization and hydrothermal carbonization. These thermochemical treatments produce porous biochar, maintained mineral components and surface functional groups as well as non-condensable gas (syngas) and condensable liquid bio-oil by the elimination of volatile material and moisture content (Tan et al., 2016). Biochar consists of moisture, fixed or stable carbon, ash components, and volatile compounds. For the long-term effectiveness of biochar, aromatic structures are produced by changing the chemical environment of carbon used during the heating process. It consists of carbon and minerals with various pore sizes that are altered by changing biomass or temperature. Micropores work efficiently for high capacity absorption. Macropores are responsible for liquid-solid absorption whereas mesopores play a basic part in hydrology, aeration, bulk soil structure and movement of roots (Tan et al., 2016).

During the process of biochar production, firstly hydrogen and oxygen are lost, and compounds such as tar-rich vapors, H_2, CO, CO_2, and hydrocarbons are formed. N is volatilized, and at high temperature, Ca, Mg and Si are released. Cl and K are vaporized at low temperature. The produced biochar thus has a higher content of P, Fe, S and Mn (Tan et al., 2016). Slow pyrolysis produces an equal amount of solid, liquid and gas by-products under slow heating rates. Under atmospheric pressure, partial combustion of biomass is carried out by hot-gas recirculation and different external heaters. Various types of reactors are used to make biochar, but a typical type of slow pyrolysis reactor works better under optimized heating integration, low temperature, low heating rates, long vapor and solid time, high pressure and long vapor residence time that vary from few hours to days. High lignin and ash containing biomass produce a higher yield of biochar. Above mentioned conditions increase the cracking reactions and lower the bio-oil yield and syngas formation. It is a useful, inexpensive method for low scale biochar production. Fast pyrolysis is carried out at fast heating rates

and moderate temperature with short residence times. The resultant product contains 75% bio-oil, 13% gases and 12% biochar.

In pyrolysis, at a high temperature (700–800 °C) biomass containing carbon under steam or controlled oxygen environment is reacted to get small hydrocarbons, hydrogen, CO_2, and CO. The resultant gas has 85% syngas, 10% biochar and 5% aromatic hydrocarbons. Gasification of lignin or cellulose-containing biomass is usually carried out in entrained-flow-bed systems, fluidized bed, and fixed bed gasifier. Gasifiers are fixed at a place and gas is passed through the carbon source (Qambrani et al., 2017). After the synthesis of biochar, the adsorbent is analyzed for nitrogen, carbon, sulfur, and hydrogen (CHNS) contents. Thermal gravimetric analyzer measures the kinetics of the absorbent at a higher flow rate. Firstly, a blank run is performed under similar conditions as followed by the procedure. After that, samples are placed in the balance, passage of nitrogen gas by mass flow controller occurs at 120 °C for 3 h to remove volatile compounds and then carbon flows at a higher rate at 25 °C. Once CO and CO_2 start to flow, the baseline measurement is performed. After 3 h, gas is again switched to nitrogen at 120 °C for 3 h for desorption of CO_2. Regeneration efficiency is calculated by dividing the remaining mass of CO_2 and CO_2 captured. Absorption and desorption after regeneration give the details of the stability of adsorption capacity. Continuous measurement of weight gives the details of CO_2 captured (Creamer et al., 2016). Studies have shown the sequestration of 200 million metric ton annually by biochar and slash and char methodology to the soil (Galinato et al., 2011). Civil infrastructure can also be a source to capture CO_2. A mixture of biochar into the cementitious material can help in reducing GHG concentration. Biochar will absorb CO_2 from the atmosphere in carbonate mineral form. Using biochar in road construction and buildings can additionally reduce the GHG by 25% (Gupta et al., 2018).

3.7. Charcoal as a carbon adsorbent

Porous carbonated materials like charcoal due to their chemical stability, good adsorption capabilities, thermal stability, recyclability and lower cost are ideal for controlling pollution through carbon adsorption. Charcoal plays a vital role in capturing carbon, and it is simply produced in a compact charcoal forming kiln. The temperature is maintained by induction heater and is monitored efficiently by the temperature sensor during pyrolysis. Carbonization and activation are usually carried out at high temperature. After this, it is ground and allowed to cool at room temperature. CO_2 is captured into this activated charcoal by adsorption. Pre-absorption is performed to ensure 100% passage of CO_2 at a 40 cm Hg pressure in the absence of vacuum. After this, the respective sample is analyzed by gas chromatography (GC). Post absorption is carried out in the presence of vacuum and analyzed by GC. The difference in the peaks of chromatogram gives the details of the CO_2 absorbed during the process (Huang et al., 2015).

4. CO_2 separation methods

Several methods have been developed for capturing flue gas from the industries. Following are the key methods for CO_2 separation.

4.1. Absorption

Physical absorption is usually applied in coal-fired power plants, acid gas separation, and natural gas treatment plants. It is carried out by the passage of flue gas through the solvent and is stripped off to get CO_2 whereas the solvent is recycled. In this technique, chemical properties remain the same while the electrostatic, and the van der wall forces act as attractive forces. Low temperature and high pressure are the prerequisite conditions for efficient adsorption whereas for desorption it is vice versa following the Henry's law's principle (Theo et al., 2016). Ionic liquids can also be used as a solvent due to their recyclability, non-flammability, low volatility and liquid nature at room temperature. These are called as designer solvents due to adjustable physiochemical characteristics. Higher capital cost, more diffusivity, and less viscosity render their efficiency (Theo et al., 2016). Composites of methanol and spherical nanoparticles of Al_2O_3 and SiO_2 are used as an absorbent. Ultrasonication is carried out firstly by adding the powdered particles into the methanol and later for the stability of absorption-regeneration, several techniques such as hydrodynamics, the bubbling of gas, inflow, and convention are employed. For absorption, at natural gas combined cycle power plant, micro-sized calcium oxide particles obtained by calcination for 3 h at 896 °C is applied. The water residues are fixed for enabling extrusion by extrude plunger at low pressure. The product is again calcined in pellets form. Immobilization of calcium oxide can also be employed as an absorbent. Nano-particulate calcium carbonate is prepared in ethanol by ultra-sonication. The suspension formed is dropped by a pipette onto the dried ceramic fabric. The fabric is then dried at 100 °C and sintered at 800 °C. The zn-cyclen enzyme is also used as an absorbent, in which perchlorate salt of zinc and the aza-macrocyclic scaffolds mixed and heated up to 60 °C. Ethanol is added to 5 ml of the prepared mixture and 10 ml of $Zn(ClO_4)_2$ in the molar ratio of 1:1. The product is then vacuum filtered and washed with ethanol several times. MS and H1 NMR 400 can verify the completion of the process (Sreedhar et al., 2017).

4.2. Cryogenic distillation

This process aims to separate CO_2 on the basis of boiling points from the gaseous mixture at an optimum temperature of −100 °C to −135 °C. Solidified CO_2 being compressed at higher pressure (100–200 atm), provides two significant advantages such as the absence of solvent and liquefied CO_2 production, which make transportation and injection more feasible (Leung et al., 2014). However, like other processes, it has some drawbacks where further research is required. For example, ice formation leads to derailed equipment safety due to fluctuations in pressure and blockage of pipes, and high-cost due to extreme energy consumption (Leung et al., 2014; Knapik et al., 2017) in which pressurized and cold nitrogen is used as a refrigerant. This has improved the CO_2 separation and has removed the refrigerant makeup and storage systems (Knapik et al., 2017; Tan et al., 2017) have used the method of cryogenic distillation for separation of CO_2 combined with the upgrading of biogas.

4.3. Physical adsorption

Zeolite is a crystalline aluminosilicate material that has a microporous structure, high stability, and adjustable catalytic site. It is one of the most widely used catalyst and physical adsorbent having micron-sized particles. It is synthesized through a hydrothermal method that is employed to get zeolite pellets like structures having the better mechanical strength (Choi et al., 2009). This possesses certain limitations when used in bed reactors such as loss of material, high mass transfer, and pressure drop. However, these issues can be overcome by using various other structures such as honeycomb, foams, and sponges (Li et al., 2009). Honeycomb is the most preferred structure due to less pressure drop, higher geometric surfaces, and less diffusional distance. Significant limitations of honeycomb structures are the decreased catalytic efficiency and less mechanical capacity (Li et al., 2009).

4.4. Carbon-based adsorbent

The adsorbent choice depends upon various parameters such as CO_2 capacity, desorption and adsorption temperature, and kinetics. An adsorbent containing all these qualities is still under development (Choi et al., 2009). High-pressure carbon capturing is achieved through, coal, activated carbon and charcoal applications. There are various sources of activated carbon such as industrial byproducts, coal, wood and many other biomass sources. Their properties such as pore structure, size and

surface area can vary with respect to the raw material. Activated carbon preparation is a two-step process. During carbonization, the precursor material is heated and pyrolyzed in an inert atmosphere. N_2, O_2, H_2 and many other non-carbon elements are released. It is then followed by the activation in which material containing carbon is modified. Both physical and chemical treatments are carried out resulting in carbon material having greater surface area and porosity. Physical process involves the passage of CO_2 steam at 1100 K-1250 K for partial gasification. In chemical processes, at low temperature, pore size is adjusted with the help of chemicals like $ZnCl_2$, H_3PO_4, and KOH (Choi et al., 2009). Due to electrical power uniformity on the surface of activated carbon, it possesses less enthalpy of adsorption than zeolite at low pressure (Ben-Mansour et al., 2016). However, the case is reversed at high-pressure that explains the 60–70% efficiency for pre-combustion as compared to 10–11% for post-combustion by weight (Ben-Mansour et al., 2016; Martín et al., 2010).

4.5. Membrane separation

Membrane separation is also used for separation of CO_2. The innovation of ceramics, metallic or polymeric membrane has made this process approximately 90% efficient. The basic principle of this technique lies in the bonding of composite polymeric layers. One of them is thin and selective, and other is mechanical support providing non-selective, cheap and thick membrane. These allow CO_2 to pass while excluding the all other components from the flue gas. This methodology can also be used for the O_2 and N_2 separation from natural gas. However, low pressure and concentration of flue gas can reduce the efficiency of the process (Leung et al., 2014). Zhai and Rubin (2013) have used the single and multi-stage configuration for the performance analysis on CO_2 separation. The multi-stage framework was 90% efficient in achieving more than 95% product purity at a coal power plant.

4.6. Chemical looping combustion

Several metal oxides such as CuO, Mn_2O_3, NiO, and Fe_2O_3 are used instead of pure oxygen in oxyfuel combustion. During this process, the metal oxide is transformed into a metal, and the fuel is converted into oxidized form as water and CO_2. Metal content is recycled, and water is collected easily by condensation while CO_2 is obtained without energy utilization. Several inert materials are used for the optimization of metal oxide depending upon its type. In this technology, the interconnection of two fluidized bed with a boiler can increase the efficiency. In a comparison of pre-combustion and chemical looping combustion, later one is 2.8% more efficient (Leung et al., 2014).

5. CO_2 transport and storage techniques

The CO_2 transportation method through road, ship, and pipelines, and selection of storage site depends upon the CO_2 volume after compression (Leung et al., 2014). It also depends on the economic situation of the region. For example in China, the cost per ton is 7.48 USD for ship tanker, 12.64 USD for road tanker and 7.05 USD for a pipeline for 300 km. Ship transportation is a reliable method for offshore transmission. However, according to Svensson et al. (2004) pipeline is a comparatively better method for longer distances. From pipelines, it is transferred in liquid or supercritical form. The supercritical form is feasible due to the maintenance of > 32.1 °C, and > 72.9 atm conditions (Johnsen et al., 2011). Recompression stations are added to offset the pressure drops. Large diameter pipeline is expensive but more suitable to avoid faster flow rate and pressure drops, and ultimately fewer recompression stations are needed (Leung et al., 2014).

Impurities affect the temperature and pressure requirements (Rabindran et al., 2011). Fluctuated water concentration (above 50 ppm) can lead to the carbonic acid formation and ultimately leads to corrosion. Moreover, hydrates formation can also cause problems in the working of compressors and valves. Maximum corrosion of the carbon steel is 10 mm per year. Pipelines nowadays are utilized for the enhanced oil recovery purposes. Canyon reef career is the oldest pipeline in Texas USA that is 225 km. The most extended pipeline is Cortez (800 km) that transports 20 million tons of CO_2 annually from a natural source (Leung et al., 2014). Managed pipeline network can help in reducing the transportation cost.

Storage of CO_2 is one of the essential methods for the reduction of global warming (van der Zwaan and Smekens 2009). Under the earth crust, CO_2 can be stored for thousands of years assuring the 0.1% leakage per year. Individual components such as mineralogy, pore fluid dynamics, fractures, geochemistry, alternation in the geochemical effects of precipitation and dissolution can affect the CO_2 behavior in the reservoir. For long-term and large storage of CO_2, the storage site should be porous, permeable, and the rock caps should be impermeable. Comparatively, oil fields are the best site, but if many wells are penetrating the field, it leads to damages.

The most prominent trapping mechanism of CO_2 is structural or stratigraphic trapping. In this method, the CO_2 is injected in the high-density free form in order to control the slow diffusion – except through faults - into the caprock that, it except through faults or slow diffusion cannot incorporate into the caprock, beneath the lithosphere. Residual trapping involves the displacement of the water as it flows down through the porous rock. And by its continuous flow, the displaced water returns, disconnects and trapping of CO_2 occurs within the pore spaces. Solubility trapping reduces the volume of CO_2 and increases the density of brine by getting dissolved in it. Mineral trapping is a relatively long process, and it involves the chemical reactions of CO_2 with minerals and saline water. This produces carbonates that can be stored for thousands of years (Amouroux et al., 2014, Zhang and Huisingh, 2017).

5.1. Underground geologic storage

Geologic storage because of site accessibility, economic aspects and many other concerns are considered as a comparatively more competent method for long-term storage of CO_2. Saline aquifers are the most suitable storage site, especially in highly populated countries. These sites cannot be used for other applications. However, due to capital problems for its implementation, it is less preferred in many countries. All the saline aquifers have the depth more than 1 km that is taken as a sedimentary basin, having higher permeability and pore size, making less pressure dissipation issue and can reduce the use of injectors by accommodating a large amount of CO_2. Supercritical CO_2 when injected displaces the pore water and reacts with the rock, groundwater, and gases. Consequently, many different minerals are formed altering the capacity or porosity of the rock.

5.2. Depleted oil and gas reserves

Hydrocarbon storage sites is an efficient, cheap, permanent and safe method for CO_2 storage (Underschultz et al., 2011). These reservoirs are deep and can store an enormous quantity of CO_2 leading to less subsurface resource contamination. Since oil and gas are preserved under increased pressure (i.e.70 MPa) and temperature (i.e.175 °C), so it is feasible for CO_2 to be in supercritical liquid form. There are mainly four trapping mechanisms such as mineral trapping, solubility trapping, capillary trapping and structural trapping (Raza et al., 2016). Capillary trapping is used when the storage site is porous. In it, CO_2 is converted from the mobile phase to an immobile phase (Jalil et al., 2012). Solubility trapping involves dissolving CO_2 into the salt solution and storing resultant dense solution. Mineral trapping involves the reaction of the saturated solution with the storage site (Raza et al., 2016). In structural trapping, CO_2 is stored and is ceased underground by the impermeable cap when its plume moves upward (Espie, 2005).

5.3. Enhanced industrial production

CO_2, in the form of a supercritical fluid, has low density and viscosity, and thus plays a significant role in the extraction of oil (Zhang and Huisingh, 2017). Exhaust gas recirculation (EGR) is an essential mechanism for increasing the natural gas production. When CO_2 is injected into the reservoir it pushes the natural gas upward (Jeon and Kim, 2015), however, this method is in the developmental stages (Khan et al., 2013). Supercritical CO_2 can also be utilized for heat exchange in the enhanced geothermal system. In the 1970's first enhanced geothermal system (EGS) project was started at Los Alamos, New York (Xu et al., 2016a,b). Mineralization of CO_2 also gives a leakage-free option for CO_2 storage due to thermodynamically stable nature, and formation of solid carbonate (Kainiemi et al., 2015). Coal matrix's higher porosity makes it more appropriate adsorbent. Coal has more affinity towards trapping gaseous CO_2 than methane. So, CO_2 when injected is permanently stored by replacing the already adsorbed methane and enhancing methane production. Some technicalities for efficient storage are minimal faulting, concentrated coal geometry, optimal depth range, adequate permeability, and reservoir homogeneity.

5.4. Basalt formation and deep ocean storage

Igneous province occupied with deep basalt formation can also provide a large room for CO_2 storage. About 8% of the continent and large areas of the ocean floor has basalt rocks. Presence of metallic divalent ions and high reactivity of these rocks make these areas a proficient storage site. At about 40 °C, oxides will consume calcium and can limit the production of ferromagnesium carbonates and siderite. On the other side, at 60–100 °C, magnesium, ankerite, and siderite will be formed. The reaction of both hydration and carbonization cause blockage of pores and many solids leading to a reduction in the stored CO_2. But the most prominent uncertainty lies in the caprock layer, and the fractures can cause many problems. For instance, sometimes the CO_2 transforms into a mineral before it reaches deep underground. So, extensive information is needed to employ this method. The ocean is 70% of the Earth crust with a depth of 3.8 km and is the most viable carbon sink. Two methodologies are adopted; one is the direct discharge of liquid CO_2 into the seawater forming droplet plumes, and the second is the injection of CO_2 into columns. The reaction of CO_2 with seawater forms hydrates, however, the criticism on the process is based on the acidification of the ocean. The parameters used to monitor the efficiency of this approach include retention time, storage depth, distribution of CO_2 and injection depth. An average depth of 1000 m is necessary, and 50 years of continuous injection can lead to 10% loss back into the atmosphere (Aminu et al., 2017).

5.5. CO_2 leakage and monitoring

CO_2 leakage, during storage or transportation, leads to many disastrous issues such as acidification of soil and ocean. Leakage can happen either through permeable pathways or cap rocks. It can occur due to the fractures and faults in the earth crust. In comparison, leakage through cap rock is slow and takes many decades. The pressure of the cap rock should be maintained before and after injection. For safe and long-term storage, the area should be monitored throughout the pre and post CO_2 injection process. The geological storage area is monitored by several methods such as temperature logs, remote sensing, geometric method, geochemical sampling, atmospheric monitoring and gravimetric methods. It is, nowadays, one of the primary focus of research in the field of climatology (Leung et al., 2014).

6. Conversion of atmospheric CO_2 into value-added products; challenges and perspectives

The captured atmospheric CO_2 can be used as a raw feedstock in various commercial, domestic, and industrial applications and for energy production. The production of biofuel from sequestered CO_2 phases out the requirement of fossil fuel. In industry, the captured CO_2 could be used to improve oil/gas recovery system, produce and recycle several chemical and rubber products, treat wastewater, use as a refrigerant, and coolant in fire extinguishers, and use for mineralization. Currently, almost negligible captured CO_2 is used in the industrial production of beverages, urea, and food preservation; leaving behind a significant room of research and development for recycling of sequestered CO_2 as raw feedstock, conserving natural resources and curbing CO_2 emissions (Markewitz et al., 2012; Al-Mamoori et al., 2017).

There is a strong need to produce biofuels like dimethyl ether and bioalcohols from the captured CO_2 due to limited CO_2 storage facilities and environmental issues of non-renewable fuel sources. For instance, CO in the syngas is converted to CO_2 that is transformed into methanol in the presence of catalysts like copper, chromium, pallaldium and zinc oxide. Furthermore, de-hydrogenation of methanol results in the formation of dimethyl ether. The sequestered CO_2 can also be employed to treat seawater and domestic wastewater against dissolved solids and conversion of brine into clean water (Al-Mamoori et al., 2017). Another promising application for the sequestered CO_2 is the production of artificially modified carbonate aggregates from steel slag. The modified CO_2 concrete competes with the conventional slags for functional strength and efficiency. For example, a 20 cm block, prepared in the aforementioned manner, could capture 2.93 kg CO_2. According to Ghouleh et al. (2017), if sequestered CO_2 is utilized in Canada's and the USA annual production of concrete, it could sequester 12 million tons CO_2 every year. Photoautotroph like algae uses CO_2 from flue gas and convert into biodiesel through transesterification, in which fluidity of algal oil is increased, and glycerol is produced. The triglyceride reaction is involved with alcohols to produce methylester and glycerol under alkaline, acidic or enzyme-based catalyst. The methylester is further mixed with conventional diesel and used as engine fuel (Adeniyi et al., 2018). CO_2 can also be converted to fuel by photocatalytic reaction of CO_2 with H_2O and H_2 along with various semiconductors like C_3H_4, ZnO, and TiO_2 (Abdullah et al., 2017).

Sequestered CO_2, from the atmosphere or flue gas, can be transformed into a high-value commodity such as carbon nanofibers (CNF). The process occurs under voltage in an electrolysis chamber that has galvanized steel cathode and nickel anode. Several carbonate electrolytes such as sodium, calcium, lithium, potassium or barium oxide are used to form molten carbonates. During the reaction, carbonate is not consumed, and CO_2 is split into pure oxygen and solid carbon. The concentration of lithium and diffusion control can alter the morphology of the product. Additional carbonates produce tangled carbon nanotubes. In the case of direct CO_2 supply, controlled electrolysis along with small additional nickel forms hollow nanotubes and nanofibers. These CNF are used in multiple applications such as a significant component in construction materials, consumer electronics, athletic equipment, vehicles, wind turbine blades and nano-electronics in making of Li-ion batteries due to their strength, flexibility, and durability (Lau et al., 2016). The application of CNF to combine cycle power plant produces pure oxygen that helps to increase the combustion process by elevating temperatures, thus resulting in improved thermal efficiency of steam and gas turbines. It also decreases the heat losses during the combustion due to diminished N_2 volume as compared to conventional power plants (Lau et al., 2016).

6.1. Current challenges

Due to an increased level of GHGs in the fast-economic development countries like India, China, USA, the climate change severity has become inevitable in the near future with the current CO_2 concentration of 408 ppm (350 ppm as a safer limit) (Kumar et al., 2017). In the arch of the energy mix, the removal of fossil fuel is very difficult that has promoted the use of carbon capture (Arranz, 2015). Economic boom

coupled with population growth has led to increased world energy demand and is expected to rise by 35% over next three decades as the primary fuel for energy generation is still crude oil (Mosavat and Torabi, 2014; Pachauri et al., 2014). One of the cheapest, widely used and the efficient source of energy is coal. It constitutes 29% of the global energy mix, accounting for about one-half of the GHG emissions. Its use in the developing countries is predicted to rise by 30% in a couple of decades (Zhao and Chen, 2015; Li et al., 2016a,b; Petrescu et al., 2017).

Increasing level of GHGs trigger the climate-induced natural disasters such as tropical cyclones, torrential rains, droughts and heat waves across the globe (Webster et al., 2005; Beiler et al., 2016). Warm climate increases the sea surface temperature and precipitation rate in tropical oceans, thus, increasing the rate and intensity of category four and five hurricanes (Lee and Ellingwood, 2017; Dinan, 2017; Bender et al., 2010). Hurricanes are among the most costly and devastating natural disasters that can cause severe damage to infrastructure and human lives through strong winds and storm surges (Solecki, 2015; Mudd et al., 2014; Michener et al., 1997). This damage is also associated with the diversity of coastal areas that make these attractive for human settlement. According to an estimate, about 70% of the world's population lives in the coastal zones. Table 3 summarizes the damage caused by major hurricanes since 1992. For the formation of a tropical storm, sea surface temperature > 26 °C, moist air and low upper-level winds are required (Webster et al., 2005; Goldenberg et al., 2001). In 2012 hurricanes claimed 143 lives in the USA with substantial economic loss of 52 billion USD. In some studies, the estimated cost caused by hurricanes equals to 5% of the global GDP (Dinan, 2017). The economy in 2075 will be four times larger as compared to now, but the damage is expected to increase more rapidly. For instance, the cost associated with hurricanes up to 2075 and predicted damage would grow significantly. This is because the intensity of hurricanes is expected to increase by order of 10% for an atmosphere with doubled CO_2 concentration (Anthes et al., 2006).

Because of the rapid melting of ice sheets and thermal expansion of water, it is predicted that by the end of this century global sea levels will be 0.18–0.4 m higher than today. This will severely affect the people living in the coastal areas (Danladi et al., 2017; Tessler et al., 2017). According to Tessler et al. (2017), the sea level is rising at the rate of 1 mm per year, but due to low sediment flux, this rate has accelerated to 2 mm per year. Local sea level rise poses many threats to the people living in the coastal areas in the form of coastal floods, high tides, seawater intrusion in coastal groundwater aquifers and wetlands (Masciopinto and Liso, 2016). Different models were employed by Goharnejad et al. (2013) to measure the local sea level rise by the end of the 21st century, and for Karachi, it comes out to be 0.72 m. Climate change has also led to many disastrous droughts and floods on the planet earth. In 2011, a drought in Somalia occurred, and about 10 million people needed humanitarian aid, 2 million were malnourished, and 380,000 became the refugees in the camps in Kenya. Zimbabwe is facing severe economic losses as a reduction of GDP by 11% due to droughts during 1990–91. Africa is suffering many serious effects such as famine (Vicente-Serrano et al., 2012). The most recent catastrophic event is sea level rise. Small island developing states (SIDS) in Pacific are about to extinct due to sea level rise, topography, coral bleaching, coastal erosion, low elevations, and storm surges.

The extreme events further leave hundred thousand people with no other choice but to abandon their homelands and to become climate refugees or forced climate migrants. Kiribati and Tuvalu are about to extinct by 2050, leaving a vast group of climate refugees. Erosion and flood have displaced about one million people in Bangladesh (Berchin et al., 2017). Globally, there is 4–5-fold increase in the extreme events since the 1980's. According to global climate risk index (GCRI), Pakistan is the 8th most affected country facing food insecurity due to climatic variability since 1995–2014. There were severe droughts from 1999 to 2003 and floods from 2010 to 2014 in several areas of Pakistan due to climate change (Abid et al., 2016). Asia is responsible for two-thirds of total world food production. Several problems can emerge because of climate change, including an increase in the phenology, stressing marine and coastal regions, food shortage, water scarcity and warming. Warming by 3 °C can reduce the food production by 28%. (Mendelsohn, 2014). In the Himalayas, extreme temperature variation leads to the melting of glaciers that results in floods and land-sliding and making water availability inconsistent (Dehejia and Wahba, 2002). Curtailing these emissions might seem a difficult task, but it can yield fruit with collective political and social efforts from all stakeholders.

6.2. Future perspectives

There is strong need to address the political hindrances in the course of CCS implementation that results in lack of global agreements. It also slows down the planning of pilot-scale CCS projects due to multiple challenges such as public acceptance, land and physical restrictions due to food insecurity, and long-term storage of carbon (Quader and Ahmed, 2017). For instance, in China, the organizations like the World Bank, global carbon capture and storage institution and Asian Development Bank have refused to fund CCS projects due to projects risk and liability. For pre and post-combustion, CCS approaches need regular monitoring, verification, and reporting coupled with the advanced level research in many cross-cutting areas. These developments should be in the form of new reactors, development of additives, improved reactions rate for CO_2 ammonia system, the study of the micro-behavior of NH_3-CO_2-H_2O, minimization of solvent loss, capturing of acid pollutants, and multi-objective optimization of reaction processes. In addition, for

Table 3
Comparison of damage caused by the major hurricanes in term of cost and causalities since 1992.

Hurricane	Year	Category	Location	Wind speed	Storm radius	Damage	Causalities	References
Andrew	1992	5	Southern Florida	73.8 m/s	77 km	$30 billion	44	(Quinn et al., 1994; Kantha, 2013)
Katrina	2005	3	Gulf of Mexico	55.9 m/s	217 km	$108 billion	1833	Kantha 2013; Cui and Caracoglia 2016
Wilma	2005	5	Mexico, Cuba, Florida	81.94 m/s	179 km	$28.9 billion	63	Kantha 2013; Chatterjee and Mozumder 2015
Ike	2008	4	Texas		195 km	$37.5 billion	186	Kantha 2013; Chen and Curcic 2016
Irene	2011	3	North Carolina	51.40 m/s	140 km	$16.5 billion	37–49	Ng et al., 2014
Sandy	2012	3	Cuba, the Dominican Republic Jamaica, Haiti, USA, Ontario	51 m/s	280 km	$65–70 billion	147	Kantha 2013; Cui and Caracoglia 2016; Britannica 2017
Patricia	2015	5	South of Mexico	82.70 m/s	_	$ 325 million	2 direct, 4 indirect	Berg, 2016
Hermine	2016	1	Florida	31.29	_	$ 550 million	1	Berg, 2016
Otto	2016	3	Northern Costa Rica and Southern Nicaragua	44.70 m/s	_	$ 190 million	18	Berg, 2016
Harvey	2017	4	Texas	_	_	$108 billion	77	Britannica, 2017

the reduction of energy requirements, new techniques like membrane technology, acid addition, stripper carriers and dual alkali methods should be employed (Sreedhar et al., 2017).

Pre-combustion is less competitive and expensive process, but due to lesser fossil fuel availability and higher demand for hydrogen-producing technologies, it is becoming a promising substitution in the future (Leung et al., 2014). CCS employing nanotechnology, biochar, and algae have been found comparatively more productive. Nanomaterials look most promising for high sorption capacity for GHGs at laboratory scale. However, further research is required on their long-term efficiency in real scale applications (Alonso et al., 2017). In the case of microalgae, it not only captures CO_2 from the flue gas stream but the same sequestered gas can also be utilized to grow microalgae for biofuel; allowing CO_2 to become feedstock instead of a pollutant (Kumar et al., 2017; Packer, 2009). Moreover, the environmental and social impacts should be assessed besides the cost-benefit analysis of these developments using life cycle assessment (LCA) approaches.

7. Conclusions

This paper explains the technological use for the monitoring and sequestration of CO_2 in an efficient manner. The burning of fossil fuel is yet inevitable, as renewable energy sources only contribute a low share to the global energy demand. The CO_2 capture and storage (CCS) is pivotal to conserve natural resources and mitigate environmental pollution. As the complete transition to renewable energy resources may require another century. This allows the consumption of coal in an environment-friendly manner by capturing the harmful GHGs. However, there is a wide gap for further research and development in finding solutions for limitations associated with CCS such as high operational cost, poor infrastructure, and energy-intensive process. In addition, adequate policies and regulations are required to address lack of incentives and capital availability. Through global coordination for combined research and development, these issues could be addressed.

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